The Lake Superior varve stratigraphy and implications for eastern Lake Agassiz outflow from 10,700 to 8900 cal ybp (9.5–8.0 ¹⁴C ka)

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Received 10 March 2004; accepted 17 October 2006

Abstract

Glaciolacustrine rhythmites within sediment cores from Lake Superior record the regional recession of the Laurentide Ice Sheet (LIS) from 10,700 to 8900 cal ybp [ca. 9.5–8.0 ¹⁴C ka]. LIS retreat from Superior opened eastern Lake Agassiz outlets so that the rhythmites reflect the combined impacts of sediment-laden meltwater and Lake Agassiz discharge. Multiple rhythmite stratigraphies, a time series analysis of the thickness measurements, and high-resolution inorganic carbonate data demonstrate that this is an annual record (varved). The varve thickness records primarily document regional ice margin dynamics; correlative thick varve sequences at 9100 cal ybp [∼ 8.1 ¹⁴C ka] and 10,400–10,200 cal ybp [∼ 9.2–9.0 ¹⁴C ka] record two periods of enhanced glaciofluvial discharge, most likely moraine formation (the Nakina and Nipigon). General varve cessation is associated with the circumvention of Lake Agassiz and glacial meltwater into Lake Ojibway at 9040 cal ybp [∼ 8.1 ¹⁴C ka], although adjacent to the inlets from Lake Nipigon, rhythmic sedimentation persisted for 200 years.

Positively identifying Lake Agassiz catastrophic discharge events remains speculative but seems feasible. Following retreat of Marquette ice that had re-advanced to fill the basin, the initial influx of Lake Agassiz water is expected at around 10,600 cal ybp [∼ 9.4 ¹⁴C ka], but at this time, most of northeastern Lake Superior was covered by ice. Three sets of thick–thin varves in western Lake Superior perhaps record influxes of Lake Agassiz at around 10,630, 10,600, and 10,570 cal ybp [∼ 9.4 ¹⁴C ka]. Varve formation in Superior coincides with high lake levels in Lake Huron, suggesting that high lake levels in Huron correspond to periods of high Agassiz and/or meltwater flow into Lake Superior.

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Keywords: Lake Superior; Lake Agassiz; Varves; Glaciolacustrine sedimentation; Carbonate sediments

1. Introduction

The sediments of Lake Superior include a sequence of rhythms that should provide an annual stratigraphic record of eastern Lake Agassiz discharge and regional deglaciation (Fig. 1A–E). Such a record would uniquely detail the flux of Lake Agassiz and ice sheet water into the St. Lawrence Seaway and North Atlantic Ocean: discharges which may have been great enough to disrupt North Atlantic Deep Water formation and precipitate abrupt cool shifts (Broecker et al., 1989; Clarke et al., 2001; Teller et al., 2002). Most of the core-based studies of the Lake Superior rhythms were conducted in the 1960s and 1970s, and researchers never associated sedimentation in the basin with Lake Agassiz discharge (Zumberge and Gast, 1961; Farrand, 1969a,b; Dell, 1971, 1972; Lineback et al., 1979). Farrand (1969a,b) generalized the stratigraphy and described Superior’s light–dark couplets as varves, but a lack of dateable organic matter
within the rhythmites precluded the possibility of using radiocarbon dates to assert their annual nature. Based on mineralogical analyses, Dell (1972) demonstrated rhythmite provenance with regional tills. She also documented measurable differences in both carbonate abundance and calcite:dolomite ratios within the light–dark couplets, and suggested that reduced sedimentation rates in the dark “winter” layers led to dissolution of the carbonates relative to the light “summer” layers (Dell, 1973).

Teller and Mahnic (1988) is the only study that attempted to connect Lake Agassiz discharge to sedimentation in the basin. Utilizing land-based drill cores from meltwater channels between Nipigon and Superior, they recognized thicker sets of rhythmites and assumed these thicker rhythmites correlated to increased Agassiz discharge. However, Agassiz overflow shared channels with ice sheet meltwater. Thorleifson and Kristjansson (1993) argued that Agassiz overflow would
have tapped sediment-poor surface water, whereas glacial meltwater would have carried immense quantities of sediment, therefore the thickness patterns noted by Teller and Mahnic (1988) reflect ice margin dynamics, not Agassiz overflow. For these reasons, it is impossible to associate any rhythms with Lake Agassiz discharge based on rhythm thickness measurements alone.

The continuous sediment record from Lake Superior could greatly refine our understanding of Lake Agassiz’s history if the record were proved to be annual and if the influences of glacial meltwater and Agassiz overflow could be identified and separated. Based on correlated rhythmite stratigraphies, associated statistical analyses, and detailed inorganic carbonate data, I assert the varved nature of the Superior rhythms. Furthermore, Lake Superior’s record is combined with the most reliable dates for eastern Agassiz overflow and Lake Huron’s coeval sediment record, to evaluate our current understanding of the recognition of Lake Agassiz discharge in sediment records from the upper Great Lakes.

2. The Lake Superior–Lake Agassiz connection

Ice first withdrew from Lake Superior sometime after 14,300 cal ybp [12.3 14C ka], which opened eastern Lake Agassiz outlets north of Thunder Bay at around 12,000 cal ybp [10.8 14C ka] (Teller and Thorleifson, 1983, 1987; Teller, 2001). Prior to this period, Agassiz drained via a southern outlet along the Minnesota/Dakota border. The Marquette re-advance, ca. 11,500 cal ybp [10.0 14C ka] (Lowell et al., 1999), filled most of the Superior Basin with ice, isolated Lake Agassiz from the Great Lakes (unless already isolated by isostatic rebound and/or a lower northwest outlet), and left a red till of variable thickness across most of Lake Superior (Fig. 1A) (Farrand and Drexler, 1985).

Drill cores from Lake Superior taken in 1961 and 1962, which have not been preserved, penetrated lacustrine sediment underlying till that likely extends back to the initial opening of eastern Agassiz outlets (Zumberge and Gast, 1961; Farrand, 1969a; Farrand and Drexler, 1985), but the oldest sediments presently available begin with the retreat of Marquette ice from the lake. Basal post-Marquette sediments are subglacial and/or ice proximal massive red sands or clays; additional ice retreat resulted in more distal, red, proglacial rhythms. There are at least 300 red, sand/silt couplets, but the total number of rhythms is site specific because the rhythms were deposited in front of what likely was an oscillating, but generally receding ice margin. Ferric oxides from local red bed sedimentary sandstones, mafic igneous bedrock, and older glaciola-crustine clays were responsible for the red coloration of the rhythms (Farrand, 1969a; Dell, 1972). Retreat of the ice sheet to the northeast, over the contact with the granite–greenstone terrane of the Superior Province (which roughly trends along Superior’s northeast shoreline), resulted in the loss of ferric source rock and sediments, and created a transition to gray rhythms (Farrand, 1969a; Dell, 1972). The more distal gray rhythms are finer-grained (averaging 92% finer than 1μ) and distinguished by light/dark color contrasts rather than by grain-size (Farrand, 1969a; Dell, 1972). Abruptly capping the rhythms are postglacial homogenous clays, gray in the eastern basins and brown in the western basins. With rhythmite cessation, sedimentation rates drop by at least an order of magnitude (Breckenridge et al., 2004).

Rhythmites were accumulating in Lake Superior when a post-Marquette Lake Agassiz eastern outlet first opened west of Lake Nipigon (the Kaishk channels), while Agassiz was at the Upper Campbell level (Fig. 1B).

Fig. 1. Late-glacial paleogeography. Ice sheet reconstructions adapted from Dyke et al. (2003) and Great Lakes paleohydrology adapted from Lewis and Anderson (1989), unless otherwise noted. (A) The Marquette advance closed eastern Lake Agassiz inlets by 11,450 cal ybp (10.0 14C ybp) (Lowell et al., 1999). Glaciofluvial outwash flowed across the Upper Peninsula of Michigan via the Au Train–Whitefish Channel (AWH). Lake Michigan (Early Lake Chipewa), overflowed via the Mackinac River. A proglacial lake in the SE Superior basin is thought to have overflowed into Lake Huron’s North Channel, via the St. Mary’s River (SMR). Georgian Bay (Early Lake Hough) overflowed into the Nipissing basin. (B) Ice retreat opened the Kaishk channels west of Lake Nipigon (KAI) and lake levels dropped in Lake Agassiz (Teller and Thorleifson, 1983; Leverington and Teller, 2003). Lake Superior (Lake Minong) overflowed into Lake Huron (Early Mattawa) via the St. Mary’s River (SMR). Huron also received direct glacial meltwater from the north. High Mattawa lake levels were maintained by hydraulic damming at the Rankin constriction on the Ottawa River (RAN). (C) Lake levels drop to Early Stanley levels in the Huron basin, perhaps coincident with ice advance to the Sioux Lookout moraine in NW Ontario, which would have closed eastern Lake Agassiz outlets (Thorleifson, 1996). This requires Lake Agassiz outflow to return to the southern outlet to initiate the Lower Campbell level. (D) Ice retreat re-opened Lake Nipigon outlets for Lake Agassiz at around 10,400 cal ybp (~9.3 14C ka), and lake levels rose again in the Michigan and Huron basins to initiate the Main Mattawa highstand. The northernmost Lake Agassiz outlet channels, the Pikitigushi (PIK) is drawn (Leverington and Teller, 2003). The Nipigon moraine and correlative ice margin is dashed, and a suggested date between 10,200 and 10,400 cal ybp is noted (this study). (E) Ice retreat allowed Lake Agassiz water to circumvent Lake Superior and coalesce with Lake Barlow–Ojibway, initiating the Ojibway phase. This is believed to correlate with general varve cessation in Lake Superior around 9040 cal ybp (~8.1 14C ka), perhaps shortly post-dating the formation of the Nakina and Agutua moraines (Breckenridge et al., 2004). Low Late Stanley levels occurred in the Michigan and Huron between around 8900 and 8200 cal ybp [8.0–7.4 14C ka] (Moore et al., 2000; Odegaard et al., 2003).
The youngest dates on the Upper Campbell shoreline are around 10,550 cal ybp [9.35 14C ka] (Risberg et al., 1996; Mann et al., 1997; Teller et al., 2000). Sometime thereafter, this eastern outlet closed, either by re-advance of the Rainy Lobe to the Sioux Lookout moraine or by differential isostatic rebound, and Agassiz outflow briefly returned to the Minnesota/Dakota border (Fig. 1C) (Thorleifson, 1996; Teller, 2001; Leverington and Teller, 2003). This transgression created the Lower Campbell shoreline, which nearly converges with the Upper Campbell at the southern outlet, but diverges to the north by more than 20 m because of isostatic rebound during the interim period of eastern Agassiz drainage (Rayburn, 1997). An anomalously negative oxygen isotopic anomaly in the Gulf of Mexico around 10,250 cal ybp [∼ 9.1 14C ka] may record the return of Agassiz drainage to the southern outlet (Aharon, 2003), but this interpretation conflicts with radiocarbon dates from the southern outlet that suggest southern Lake Agassiz overflow ceased completely at around 10,600 cal ybp [∼ 9.4 14C ka] (Fisher, 2003).

In the Superior basin, subsequent ice retreat that followed the initial drawdown from the Upper Campbell level in Lake Agassiz re-opened eastern Agassiz outlets into Lake Superior and exposed a succession of outlet channels west of Lake Nipigon (Zoltai, 1967; Teller and Thorleifson, 1983, 1987; Leverington and Teller, 2003). Complicating the retreat history are at least two ice advances to the Nipigon and Nakina moraines (dashed lines, Fig. 1D and E), which never blocked eastern Agassiz drainage, but may have overrode lower outlet channels and temporarily raised Lake Agassiz. Many Lake Agassiz water planes are recognized during eastern drainage into Superior, and multiple catastrophic drawdown events have been predicted. The initial drawdown event from the Upper Campbell level and a much later drawdown event from the Stonewall level are thought to have been the two greatest (Teller et al., 2002; Leverington and Teller, 2003).

Paleomagnetic secular variation (PSV) records from Lake Superior’s postglacial sediment records provide dates for the cessation of glacial meltwater into Lake Superior (Johnson and Fields, 1982; Mothersill, 1988). A re-evaluation of many PSV records, and a recognition that there are correlatable rhythmites, yielded a date of 9040±80 cal ybp [∼ 8.1 14C ka] for ice recession north of the Hudson Bay–Great Lakes drainage divide, when both Agassiz and LIS meltwater must have begun circumventing Lake Superior (Breckenridge et al., 2004). Between initial eastern meltwater diversion around 10,600 cal ybp and final diversion into Ojibway at 9040 cal ybp, Agassiz beach ridges, outlet channels, and ice margin positions have not been temporally constrained.

3. The correlative Lake Huron record

Well-studied, temporally correlative sediment records from Lake Huron, as well as extensive seismic reflection surveys, document fluctuating water levels following the Marquette ice advance into Lake Superior (Rea et al., 1994a,b; Moore et al., 1994; Dettman et al., 1995; Moore
et al., 2000). Two highstands (the Early and Main Mattawa phases) punctuated three lowstands (the Early, Middle, and Late Stanley phases). During this entire period, Lake Huron drained via northern outlets into the Ottawa River, and received water from Lake Superior via the St. Mary’s River, and from Lake Michigan via the Mackinac Straits. During the initial lowstand, the Early Stanley, Lake Huron also received glacial meltwater from overland ice sheet drainage to the north (Fig. 1A). Early Stanley sediments include approximately 300 red–gray glaciolacustrine varves (basal laminae are red), succeeded by tri-color, millimeter scale laminae that grade into homogenous brown or reddish-brown clay (Rea et al., 1994a; Godsey et al., 1999). Lake levels rose during the short-lived, Early Mattawa highstand (Fig. 1B), which is contemporaneous with the Upper Campbell drawdown at ∼10,600 cal ybp from Lake Agassiz into Superior (at least within the margins of error produced by radiocarbon dates). This highstand is interrupted by the Middle Stanley lowstand (Fig. 1C). The Stanley lowstands are characterized by coarser-grained sediments (although median grain sizes are always clay at offshore sites), and seismic sequence boundaries, which appear as erosional surfaces (Rea et al., 1994a; Moore et al., 1994). Lake levels rose again around 10,400 cal ybp [9.3 14C ka] during the Main Mattawa (Fig. 1D) (Moore et al., 2000). The highest Main Mattawa lake levels were not maintained by local sills in the Huron Basin, but by hydraulic damming at the Rankin constriction within the Ottawa River (Lewis and Anderson, 1989). Main Mattawa sediments are clays that grade from reddish below (sometimes rhythmically laminated) to gray above, in a manner similar to the color sequence within the Lake Superior rhythmites (Rea et al., 1994a). Roughly synchronous, or shortly after the cessation of varves in Lake Superior, lake levels fell again in Huron, to Late Stanley levels (Fig. 1E), which reached an ultimate lowstand at around 8400 cal ybp [7.6 14C ka] (Moore et al., 2000; Odegaard et al., 2003).

4. Methods

The primary sediment records reported herein originate from two Kullenberg piston cores (9.3 and 11.1 m in length) taken from Caribou Basin during the summer of 2002 aboard the R/V Blue Heron (BH02-3P and BH02-5P) (Fig. 2). Black and white photographs (taken by W. Farrand in the 1960’s) were used to correlate S62-8, a punch-core/wire line drill core that penetrated bedrock (Zumberge and Gast, 1961), to BH02-3P and-5P. Rhythmite thickness records from Kullenberg cores taken from western Lake Superior, LS00-3P, and from two overlapping cores, BH01-6P/8P, located southwest of the Slate Islands, are also reported (Fig. 2). All cores were logged at the Limnological Research Center in Minneapolis with a Geotek Multi-Sensor Core Logger (MSCL), split into working and archive halves, and photographed with a flatbed digital core scanner. The MSCL measures whole core, volume magnetic susceptibility (K) and wet bulk density via gamma ray attenuation. Wet bulk density and kappa values co-vary within the rhythmites in BH02-5P, so whole core, mass normalized magnetic susceptibility ($\chi_m$) was approximated by dividing kappa values by the wet bulk density data. Rhythmite thickness and grayscale intensity were measured from digital images with Sigma Scan Pro image

![Fig. 3. Rhythmite images from BH02-5P, scale in centimeters. A) Thick gray rhythmites near the base of BH02-5P. B) Thinner rhythmites that predominate. C) Thick rhythmites at the top of the sequence.](image-url)
Fig. 4. Correlated rhythmite stratigraphies (left) and the contemporaneous record from Lake Huron after Moore et al., 2000 (right). Cores are correlated to calendar years before 1950 (far left), with radiocarbon ages at the far right. Because of the irregular shape of the radiocarbon calibration curve, there can be multiple intercepts for radiocarbon ages converted to calendar years. I plot 1-σ distributions of the radiocarbon calibration curve by Stuiver et al. (1998) at 10014C year intervals. Rhythmite thickness records and generalized lithologies are correlated from three locations: LS00-3P, BH01-6P/8P, and Caribou Basins (S62-8, BH02-3P, and BH02-5P), and also Dorion, which originates from Teller and Mahnic (1988). The Dorion record was incomplete, so additional rhythmite thicknesses were interpolated by Thorleifson and Kristjansson (1993), which is reproduced here in black. If the Dorion record was underestimated by 150 years, a better correlation is possible with Caribou Basin (shown in gray). The Huron isotope record (black) represents average oxygen isotope values from multiple sediment cores from Lake Huron. The lake level curve (gray) originates from Lewis and Anderson (1989), but was correlated to the Lake Huron sediment cores on the basis of grain size measurements and seismic reflection profiles (Rea et al., 1994a; Moore et al., 1994). Lake Huron lake stands are named, and lowstands shaded gray. Dates relevant to the Agassiz, Superior, and Huron records appear at the far left and right. Most dates are calibrated radiocarbon dates, with 1-σ ranges obtained from intercepts, calibrated with CALIB 4.3 using the INTCAL98 dataset (Stuiver and Reimer, 1993; Stuiver et al., 1998). Two dates from basal lake sediments (date “J”) and two dates on flood deposits from the Clearwater–Athabasca spillway (CLAS) (date “K”) were combined with Oxcal v3.5 (Bronk, 1995) before calibrating with CALIB. Date “D” derives from paleomagnetic records of secular variation rather than radiocarbon dates. A: terminal age from a meltwater channel, NE of Superior (Bajc et al., 1997), B: Late Stanley lowstand, Mackinac straits (Lewis and Anderson, 1989), C: Late Stanley lowstand, Bruce Mines Bog (Lewis and Anderson, 1989), D: varve cessation, Lake Superior (Breckenridge et al., 2004), E: basal sediments from Lake Alfies, post-Minong lake levels in Superior (Saarmisto, 1974), F: Upper Campbell (Mann et al., 1997), G: Upper Campbell (Teller et al., 2000), H: southern outlet spillway abandonment (Fisher, 2003), I: initiation of red varves, SE Superior (Fisher and Whitman, 1999), J: basal lake sediments on the Marquette tills (Hack, 1965), K: NW outlet flood deposits (Fisher et al., 2002), L: Marquette Advance, Gribben Forest Bed (Lowell et al., 1999).
analysis software at the University of Minnesota Duluth, Visualization and Digital Imaging Lab. The Superior rhythmites are typically graded in color, having a light-colored basal layer that grades upward into a darker top layer (Fig. 3). The contact between a basal light layer and a preceding dark layer is sharp. Rhythmite thickness was defined as the shortest distance between these sharp color contrasts. The color images were converted to grayscale, and reflectance (grayscale intensity) was calibrated with a color card that accompanied the scanned cores. The scanned images had a 0.1-mm resolution, but grayscale data were averaged over 1-mm intervals.

Subsequent lithological analyses derive exclusively from individual rhythmite samples from BH02-5P. The working half was split again lengthwise, parallel to the surface of the core, and every rhythmite individually sampled (1406 samples). Samples were freeze-dried and powdered prior to analysis. Total inorganic carbon (TIC) concentrations, measured on a UIC model 5011 CO₂ coulometer after acidification with 2N hydrochloric acid (Engleman et al., 1985), are reported from approximately every 12th sample.

5. Results

5.1. Core correlation and rhythmite thickness

Rhythmite thickness records are correlated between four sites: “Dorion”, LS00-3P, BH01-6P/8P, and Caribou Basin cores BH02-3P, BH02-5P, and S62-8 (Figs. 4 and 5). This stratigraphy relies upon an assumption that they are varves, a central issue that will be addressed below. These records are correlated with either: a series of 36 anomalously thick varves at or near the top of the rhythmite sequences, or the red–gray color transition near the base of the sequence. The 36 correlative varves are an isochronous stratigraphic unit, the top of which marks the general cessation of rhythmites in all but the northern margins of the lake (date “D” in Fig. 4, Breckenridge et al., 2004). Correlation between records from Caribou Basin, BH01-6P/8P and the Dorion core are based on these varves. The Dorion record was presented originally in Teller and Mahnic (1988) as a mean rhythmite thickness record, but not every rhythmite was measured, primarily because of incomplete recovery. Thorleifson and Kristjansson (1993) produced an interpolated rhythmite thickness record based on their measurements, and this is what is reproduced herein. The assumption is that the thick rhythmites at the top of the Dorion core correlate with these 36 rhythmites that are ubiquitous across most of the lake.

The red to gray color transition is used to correlate LS00-3P to the Caribou Basin cores. Because the transition resulted from a decreasing flux of local ferric sediment, there is no reason to believe that the color transition was not generally synchronous across the basin. In BH01-6P/8P, located near the contact with the Superior Province, red rhythmites are entirely absent. Conversely there are approximately 200 red rhythmites at the base of LS00-3P. Around 100 red, sandy-silt/clay couplets are present in Caribou Basin, but LS00-3P is west of Caribou Basin, and should be an older record. In both records the red rhythmites decrease in thickness up section. In the Caribou Basin cores, the upper darker colored layers initially fade to gray, creating red–gray transitional rhythmites that are followed by gray rhythmites. In LS00-3P, rhythmite thickness steadily decreases up to a 13.4-cm unit of laminated brown–gray clay (“BGC”, Fig. 4), which is followed by thin gray rhythmites. The lack of rhythmites within this section is attributed to anomalously low sedimentation rates. The finely laminated gray–brown clay is correlated with the thin, red–gray transitional rhythmites in Caribou Basin, which are some of the thinnest couplets in the entire record.

The thickness record from Caribou Basin is augmented with measurements that detail the thickness of the light layer relative to the entire couplet (see Fig. 6, “Light:Total”). Ashley (1975) classified glaciolacustrine varves into three groups based on the relative thickness of the “summer” silt layers to the “winter” clay layers. Group I varves have winter layers that are thicker than summer layers, group II varves have layers of approximately similar thickness, and group III varves have summer layers that are thicker than winter layers. Changes in relative thickness of the two layers have been linked to distance from sediment influx (proximal vs. distal) and the relative time interval associated with winter sedimentation (Ashley, 1975; Smith and Ashley,
There are significant lithological differences between the Superior rhythmites and classical silt/clay couplets produced in proglacial lakes, but this record highlights changes in the general appearance in the rhythmites that are obvious during inspection of the core. The thicker rhythmites have equally thick dark layers (group II, see Fig. 3A), with the very thick rhythmites at the top of BH02-5P a noted exception (group III, see Fig. 3C). Most rhythmites have thinner light layers relative to dark layers (group I, see Fig. 3B), but there is a trend upsection towards rhythmites with relatively thicker light layers (group II).

A critical observation concerning the thickness records is that rhythmite thickness patterns can be locally correlated, as within Caribou Basin (Fig. 5) and between BH01-6P and BH01-8P; however, below the 36 correlative varves, correlating individual rhythmites between basins seems unlikely, at least based on thickness patterns alone. This is not surprising given the complex bathymetry of Lake Superior and the fact that there were multiple glacial meltwater inlets, which shifted through time. A primary concern is determining whether or not these rhythmites are annual, a presumption underlying the correlation. Towards this end, the rhythmite thickness records were analyzed for quasi-periodic frequencies associated with known climatic forcings.

### 5.2. Time series analysis from Caribou Basin

The thickness of a rhythmite is related to the sediment flux from the regional ice sheet, and perhaps Lake Agassiz discharge. If the regional ice margin responded to climatic forcing, and if the rhythmites were annual, quasi-periodic patterns in the rhythmite thickness time series might be expected to mimic known climatic forcings. Quasi-periodic cycles have been recognized in both instrumental and paleo-records, including solar cycles (200, 88, 22, and 11 year) (Lean and Rind, 1998; Dean, 2000), the North Atlantic Oscillation (10–6 year) (Mann and Park, 1994; Wanner et al., 2001), the El-Niño Southern Oscillation (18–15 and 6–2 year) (Mann and Park, 1994; Mann et al., 2000), and the Quasi-Biennial Oscillation (2.8–2 year) (Baldwin et al., 2001). The important question relative...
to this analysis is whether common quasi-periodic cycles exist in this time series if the rhythmites are presumed to be annual.

The stacked rhythmite thickness record from Caribou Basin was log-normalized to obtain a Gaussian distribution, more appropriate for statistical analysis; then via a multiple-taper statistical analysis (Mann and Lees, 1996), the transformed time series was analyzed for statistically significant, high frequency, narrowband signals. A “red noise” null hypothesis was used to test statistical significance. More than two times as many points exceed the 95% confidence interval than what is expected randomly (Fig. 7). If these rhythmites are assumed to be annual, the quasi-periodic frequencies that rise above the 95% confidence interval include periods of 50, 42, 25–22, 18, 11, 7.7, 6, 5, and 4–2 years. All of these frequencies have been documented within other annual records, including varves from Elk Lake (50 and 22 year), glacial Lake Huron (7, 4, and 2.6 year), and glacial Lake Hitchcock (>40, 22, 5–4, and 2.8–2.5 year) (Anderson, 1993; Godsey et al., 1999; Rittenour et al., 2000).

The existence of these patterns in the Superior rhythmite record is consistent with the notion that the couplets were annually deposited. The annual sediment flux presumably was sensitive to temperature and/or precipitation patterns; both ice sheet discharge and outflow from Lake Agassiz (which had a much larger watershed and longer northern ice margin than Lake Superior) were likely sensitive to these patterns. Because the climatic boundary conditions that precipitated these rhythmites are unique relative to today, determining causal linkages between these patterns and modern climatic phenomena is speculative and beyond the scope of this paper. However similar patterns of cyclicity are recognized within older glaciolacustrine varve records from glacial lakes Huron and Hitchcock (Godsey et al., 1999; Rittenour et al., 2000). Their existence has raised speculation that the presence of the Laurentide Ice Sheet may have created climatic teleconnections with the Great Lakes region that do not occur today. For example, the ice sheet may have stabilized atmospheric circulation patterns and the path of Pacific moisture transport to enhance the influence of the El-Niño Southern Oscillation along the ice front (Godsey et al., 1999; Rittenour et al., 2000). Their occurrence in Lake Superior is consistent with these prior interpretations and merits further investigation.

5.3. Rhythmite lithology and carbonate accumulation

These are not typical silt-clay glaciolacustrine rhythmites, but composed almost entirely of clay-sized grains. Grain size measurements conducted in the 1960s failed to recognize differences within the gray rhythmites (Farrand, 1969a), but recent measurements on the youngest varves, utilizing a laser diffraction particle size analyzer, reveal subtle median grain size variations between the light colored laminae (∼ 1 μm, 10φ) and the dark laminae (∼ 1.7 μm, 9.2φ) (unpublished data). Except for the carbonates, there seem to be no consistent mineralogical differences within the gray varves between the light and dark layers. Dell (1972, 1973) reported that on average, dark layers contain 55% less...
calcite and 39% less dolomite than light layers. She proposed that the rhythmites were “calcite solution varves,” whereby fast summer sedimentation rates prevented the dissolution of calcite in a lake that must have been undersaturated with respect to calcite. Conversely, during the ice-covered, winter months, sedimentation rates slowed dramatically, and the fine-grained carbonates would dissolve, leaving behind a winter layer with less carbonate than the summer layer.

Grayscale intensity measurements and TIC analyses on individual rhythmites support the notion that the color contrasts that distinguish the rhythmites are attributable to carbonate content (Figs. 6 and 8A). Within BH02-5P, rhythmite thickness and TIC strongly co-vary (Figs. 6 and 8B). TIC decreases with respect to thickness upsection, although this relationship can be divided into three zones: A, B, and C. Zone A includes a series of around 300 relatively thick rhythmites at the base of BH02-5P (Fig. 3A). Light layers are generally slightly thicker than the dark layers, and the color contrasts between the two layers are better defined than anywhere else in the core (note the large variations in reflectance, Fig. 6). Zone B includes most of the gray varves; rhythmites are generally thin, but thicken upsection (Fig. 3B). Dark layers are thicker than light layers, except near the top of the zone. In zone C, TIC values are low relative to rhythmite thickness. This zone includes the thirty-six correlative varves (Fig. 3C).

Strongly correlated with the TIC record is mass normalized magnetic susceptibility ($\chi_m$) (Fig. 6). Magnetic susceptibility is a function of the magnetic mineral concentration and magnetic mineral grain size. For the rhythmites, $\chi_m$ values seem to be controlled primarily by the relative concentration of the non-carbonate fraction, i.e. with increasing inorganic carbonate, $\chi_m$ decreases. The lone exception is within the 36 correlative varves, which have anomalously high $\chi_m$ values: indicating an increase in magnetic mineral concentration or a relatively greater concentration of ultra-fine, ferromagnetic grains (superparamagnetic) (Thompson and Oldfield, 1986).

6. Discussion

6.1. The annual nature of the Superior rhythmites

All recent data continue to support Farrand’s (1969a) initial notion that the rhythmites are varves. The thickness patterns are quite regular, which rules out the possibility that they were produced by infrequent storm events or debris flows. Their total number fits very well between estimated ages for the top and bottom of the varve sequence, dates “D” and “I” in Fig. 4. Date “I” is a radiocarbon date on a macrofossil from Beaver Lake, located approximately 80 km south of the Caribou Basin coring sites, along Superior’s southern shore (Fisher and Whitman, 1999). This date establishes rhythmite sedimentation at Beaver Lake at 10,710 cal ybp (9.5 $^{14}$C ka). The difference between these two dates is 1670 years and there are 1540 rhythmites in
Caribou Basin; the 130-year difference would represent the time necessary for ice retreat from Beaver Lake to Caribou Basin.

I interpret the rhythmites in Caribou Basin as varves because the rhythmite thickness patterns are regular, rhythmite counts correlate well with dates for the top and base of the sequence, and power spectra mimic those found in annual paleoclimate records. There are undoubtedly minor errors in the raw count, but in general, this seems to be an annual record. Given their probable annual origin, the mechanisms responsible for varve formation merit a more thorough discussion.

6.2. Varve formation

The color contrasts that distinguish the varves are created by differences in carbonate content (Fig. 8A) and Dell’s (1972, 1973) suggestions that the carbonate was allochthonous and that the rhythmites were caused by carbonate dissolution seem valid. She argued that glacially fed lakes, even those on carbonate terrane, are cold and dilute systems, and are not typically saturated with calcium carbonate. Biogenic carbonate is currently produced in Lake Superior, but dissolution prevents carbonate accumulation in the sediments (Thomas and Dell, 1978). A seasonal change in source between the winter and summer seasons has been invoked to explain older red–gray rhythmites in Lake Huron (Godsey et al., 1999), but that model is ruled out for Lake Superior. Cores recovered from western Lake Superior in the deep troughs also have gray rhythmites, despite the presence of local red tills and the absence of gray tills along the Minnesota shore. Furthermore, sedimentation rates dropped by an order of magnitude with varve cessation. For these reasons, the source of this sediment must be derived from the ice sheet and possibly Lake Agassiz, rather than local precipitation, and there is no reason to expect significant seasonal variability between Lake Agassiz overflow and ice sheet discharge. Instead seasonal changes in sedimentation explain the annual laminations. This process is typically invoked to explain glaciolacustrine varves, whereby sediment-laden underflows or interflows during the summer produce silt layers, and the rainout of suspended sediment during ice covered months produces clay layers (Smith and Ashley, 1985; Ashley, 1988); however in this case, the dissolution of suspended carbonate is primarily responsible for distinguishing the rhythmites rather than grain size variations. Lake Agassiz overflow, which would have tapped surface water with finer-grained sediment than glaciofluvial discharge, may contribute a relatively greater proportion of sediment to the darker layers; but co-variance between rhythmite thickness and TIC substantiate the notion that the lake was undersaturated with respect to calcite (Fig. 8B).

Glacial sediment would dilute authigenic calcite, creating a negative correlation between TIC and rhythmite thickness. The lake was also below calcite saturation, because even the most calcareous rhythmites do not have as much carbonate as the fine-grained matrix (<63 μm) from unoxidized tills north of Superior, which average around 3.6% TIC by mass (Thorleifson and Kristjansson, 1990). In BH02-5P, the relationship between carbonate and rhythmite thickness is linear, but changes abruptly between zones A, B, and C (Figs. 6 and 8B). Note that TIC does not increase in zone B when the relative thickness of the light layer compared to the total thickness increases; therefore separate carbonate-rich and carbonate-depleted sources cannot explain this relationship. The increased slopes from zone A to zone C could be achieved by increasing the amount of carbonate annually dissolved, decreasing the TIC content or the dolomite:calcite ratio of the incoming sediment, or decreasing the amount of calcareous sediment that is directly sequestered to the lake floor. If the chemistry of Lake Agassiz waters varied substantially from glacial meltwater, or if Agassiz water transported a significant amount of sediment, Lake Agassiz discharge would have affected this relationship.

6.3. Separating Lake Agassiz and Laurentide Ice Sheet (LIS) meltwater

The lower set of thicker varves in the Dorion core was previously attributed to formation of the Nipigon moraine (Thorleifson and Kristjansson, 1993; Lewis et al., 1994). Because the Nakina and Nipigon moraines were created by ice advance, and are primarily ridges of sand and gravel that are fed by numerous eskers (Zoltai, 1965), an underlying assumption is that these moraines formed during periods of anomalously high meltwater and sediment discharge following surging of the ice margin (Sharpe and Cowan, 1990). BH01-6P/8P is located near the southern terminus of the Nipigon moraine and the varves overlie well-sorted, red sands probably associated with the moraine; therefore the first varves in BH01-6P/8P should post-date the moraine. The thickest varves in the Dorion core, and the long series of thick varves in Caribou Basin, pre-date the varves in BH01-6P/8P. If the Dorion record is underestimated by 150 years, the scaled record matches Caribou Basin and BH01-6P/8P quite well (see the gray line in the Dorion record, far left Fig. 4), suggesting that
the Nipigon moraine formed between 10,400 and 10,150 cal ybp (~ 9.25–8.9 14C ka). The red–gray varve transition occurs just prior to these thick varves, which is expected, because the Nipigon moraine closely parallels the border between the Keeweenaw redbeds and granite–greenstone terrane of the Superior Province.

The Nakina moraine straddles the modern watershed divide (Fig. 1E). Isostatic depression by the ice sheet would have shifted the drainage divide to the south. Ice retreat north of the Nakina moraine would have permitted Lake Agassiz drainage to coalesce with Lake Ojibway, which drained via the Ottawa River (Dredge and Cowan, 1989; Veillette, 1994); therefore varve cessation is postulated to closely post-date the formation of the Nakina moraine. The varve record ends in most of the basin with the thick, correlative varves: suggesting these that thick varves correspond to the formation of the Nakina moraine over a 36-year period (Thorleifson and Kristjansson, 1993; Breckenridge et al., 2004). Because magnetic susceptibility ($\chi_m$) increases relative to the non-carbonate fraction and the TIC concentrations are also low relative to varve thickness, the source area for these varves is also unique. Perhaps ice advance over extensive areas of glaciolacustrine sediment, as proposed by Prest (1963) for the Agutua moraine (see Fig. 1E), diluted sediment more typically associated with the ice sheet.

Major Agassiz drawdown events may have cleared outlet channels of substantial amounts of sediment, but the events should have been less than 5 years in duration (Teller and Thorleifson, 1983, 1987; Teller et al., 2002; Leverington and Teller, 2003). Agassiz outlets would have opened before the creation of the Nipigon moraine.

Ice retreat from Caribou Basin occurred between 10,550 and 10,500 (~ 9.35 14C ka) (represented by the thick red, basal rhythmites in S62-8, that gradually decrease in thickness upsection). Based on radiocarbon dates (see dates “F”, “G”, and “H” in Fig. 4), Agassiz overflow would have occurred during the red varve sequence at around 10,600 cal ybp [9.4 14C ka], when much of the northeastern Lake Superior basin was still covered by ice (Fig. 1B). In western Lake Superior (LS00-3P), three sets of thick–thin rhythmites were deposited at around this time (Figs. 4 and 9). These varves are unique; they abruptly thicken, each with one or two thick varves, then quickly taper over the next three to nine varves: perhaps consistent with catastrophic drawdown of Lake Agassiz that rapidly diminishes with time. The ice margin was within Caribou Basin at this time, and if the Dorion stratigraphy is valid, the Dorion site was also covered by ice. If the Dorion record is undercounted by 150 years, the Dorion channel was ice-free and Agassiz overflow occurred within the gray–pink rhythmites, 100+ years before Dorion’s thickest gray rhythmites. Core recovery was less than 50% within this interval, so perhaps the thick–thin rhythmite sequences observed in LS00-3P were missed in the Dorion core.

6.4. Correlations with Lake Huron’s sediment record

The lake level and oxygen isotopic record from Lake Huron has provided the foundation for interpreting meltwater routing through the Great Lakes (Fig. 4, right). The most perplexing aspect of this record are highstands that coincide with high oxygen isotope ($\delta^{18}O$) values. The most recent studies concluded that changes in hydrology of the basins led to less negative $\delta^{18}O$ values
during highstands than during lowstands (Moore et al., 1994; Rea et al., 1994a,b; Dettman et al., 1995; Moore et al., 2000). Moore et al. (2000) argue Lake Agassiz overflow and ice sheet meltwater must be isotopically light (although they did not attempt to distinguish the two sources). They relied on data from Lake Agassiz sediments from the northern basin of Lake Winnipeg, which span the Early Stanley and Main Mattawa phases of Lake Huron (Rodrigues and Lewis, 2000). The oxygen isotopic values of benthic ostracodes within these sediments range from –17 to –23.5‰ PDB: values nearly as low as those expected from calcite precipitation in glacial meltwater. In stark contrast, Main Mattawa isotopic values range between –11 and –4‰ PDB: similar to modern ostracodes (Dettman et al., 1995). For this reason, the isotopically light lowstands were interpreted as periods of high meltwater flow, whereas isotopically heavy highstands were dominated by local precipitation and less meltwater.

Varve formation in Superior, i.e. the influx of glacially derived meltwater and sediment, coincides with high Lake Huron water levels. In accordance with earlier interpretations of the Huron lake level record (Lewis and Anderson, 1989, 1992; Lewis et al., 1994), I suggest that highstands are associated with Lake Agassiz overflow and glacial meltwater, whereas lowstands are associated with the absence of Lake Agassiz overflow and moderate glacial meltwater influx. The clearest example of this connection is during the transition to the Late Stanley lowstand.

Radiocarbon dates for the initiation of the Late Stanley lowstand in the Huron Basin around 9000 cal ybp [∼ 8.1 14C ka] correlate well with general varve cessation in Superior. These include dates on tree stumps in the Mackinac Straits (date “B”, Fig. 4) and on plant detritus from Bruce Mines Bog (date “C”, Fig. 4), which was stranded by lowered lake levels in Huron (Lewis and Anderson, 1989). Similar dates exist from South Bay on Manitoulin Island (Lewis et al., 1994; Rea et al., 1994a) and from the Nipissing Basin, including dates from Wolsely Bay, Monet Lake, and Deany Lake (Lewis and Anderson, 1989).

Seismic reflectors reveal low stands in Lake Huron, which are correlated to grain size records from sediment cores (Moore et al., 1994; Rea et al., 1994a). A coarser grain size interval associated with the “Light Blue” seismic reflector marks the Late Stanley lowstand between around 8800 and 8400 cal ybp [∼ 7.8–7.4 14C ka] (Moore et al., 1994; Odegaard et al., 2003). Strongly negative δ18O values precede the lake level drop and stay low during the lowstand in both Michigan and Huron (Moore et al., 2000; Odegaard et al., 2003), leading Moore et al. (2000) to estimate major increases in meltwater flow through Lake Huron at this time, perhaps related to backflooding of Lake Barlow–Ojibway into the Great Lakes (Rea et al., 1994b). The extreme negative isotopic shift and the lowered lake levels may be explained by correlative changes in Lake Superior’s varve record.

The extremely low δ18O values recognized in the Huron cores that pre-date the ultimate Late Stanley lowstand may have resulted from a 36-year period of thick varves and anomalously high meltwater discharge in Lake Superior beginning around 9100 cal ybp [∼ 8.15 14C ka]. In core LH91-37PC from Lake Huron, the sudden drop in δ18O values precedes the Light Blue reflector (the lowest Late Stanley lake levels) by perhaps 200 years (Fig. 14 in Rea et al., 1994a). Perhaps this event flushed Superior, Huron, and Michigan with 18O depleted water, which was eclipsed by a subsequent drastic reduction in water supply, sedimentation rates, and lake levels. Varve deposition near the Nipigon inlets persisted for 200 years following this event, but the lack of varve deposition during this period elsewhere in the lake suggests greatly diminished meltwater flux. Lake Agassiz water, along with most glacial meltwater circumvented Lake Superior. Perhaps stagnant ice persisted in the Lake Superior watershed, along with stranded proglacial lakes, including lakes Kelvin (Lemoine and Teller, 1995) and Nakina (Zoltai, 1965), which continued to drain through the Nipigon inlets into Superior. The general cessation of meltwater and Lake Agassiz overflow through Superior into Huron led to the Late Stanley lowstand, but the prolonged negative δ18O anomaly in Lake Huron sediments may reflect relict glacial meltwater in Superior that was not diluted with Lake Agassiz overflow.

Similar drastic isotopic shifts occur during the earlier Stanley lowstands. Prior to varve formation in Lake Superior, the Marquette advance would have sealed off Lake Agassiz overflow, initiated low water levels (Early Stanley lowstand, Fig. 1A), and led to water depleted in 18O in the Great Lakes, but the absence of Lake Agassiz waters would have led to lower water fluxes. Increasing lake levels and a 6‰ increase in δ18O values in Huron corresponds well with dates for initial Agassiz eastern drainage around 10,600 cal ybp [∼ 9.4 14C ka]. Shortly thereafter (∼ 10,500 cal ybp), lake levels and δ18O values drop (Main Stanley lowstand). The low lake levels correspond to some of the thinnest varves in the Superior record. Perhaps ice sheet advance closed eastern Agassiz drainage (Thorleifson, 1996), and flow returned to the southern outlet (Lower Campbell) or regional cooling resulted in very low ice sheet melting.
rates. Regardless of Lake Agassiz routing, glacially derived meltwater would have continued to flow from Superior into Huron, and perhaps overland from the ice margin into Huron’s northern basins. A return to high lake levels around 10,400 cal ybp (~ 9.25 ^14C ka) (the Main Mattawa highstand) corresponds with thicker varves in Lake Superior.

Because high lake levels in Huron, varve formation in Superior, and the chronology of eastern Lake Agassiz drainage all coincide, high Agassiz fluxes are probably associated with relatively high $\delta^{18}O$ values in Huron, as suggested previously by Lewis et al. (1994) and Buhay and Betcher (1998). Lake Agassiz baseline flow into the Great Lakes during much of the Superior varve record is predicted to have been around 0.05 Sv (Licciardi et al., 1999; Teller et al., 2002), a yearly discharge approximately one-half the volume of Lake Huron during the Main Mattawa highstand (Gareau et al., 1998). Most of this water was derived from precipitation in the Agassiz watershed, not from ice sheet melting (Teller, 1990; Licciardi et al., 1999), so it may have been substantially enriched in $^{18}O$ compared to glacial meltwater (Lewis et al., 1994). Perhaps the very low $\delta^{18}O$ values from benthic ostracodes in Winnipeg’s north basin do not reflect the isotopic values of Lake Agassiz overflow spilling into Lake Superior (and Huron). Pore water and plant cellulose analyses from Lake Agassiz sediments support speculation that Agassiz overflow was enriched in $^{18}O$ during this interval, on the order of $-7$ to $-9\%$ SMOW compared to $-25\%$ SMOW for glacial meltwater (Buhay and Betcher, 1998). This is a critical point of contention (see Buhay and Betcher, 1998), because Lake Agassiz water with higher $\delta^{18}O$ values would yield profoundly different meltwater estimates than estimated from Lake Huron by Moore et al. (2000). Unfortunately, such an interpretation remains debatable until a robust oxygen isotope stratigraphy is produced from Superior and the isotopic composition of Lake Agassiz outflow can be verified.

7. Conclusions

Multiple lines of evidence support original interpretations that the Lake Superior rhythmites are varves (Farrand, 1969a,b). Rhythmite thickness patterns are regular, but include quasi-periodic frequencies commonly associated with several modern climatic cycles. The total number of rhythmtes fits within the estimated ages for the top and bottom of the sequence. Rhythmite thickness, TIC, and grayscale patterns are all consistent with a “calcite solution” model for varve formation proposed initially by Farrand (1969a) and Dell (1973). Because this is a varved record, inferences regarding ice sheet dynamics and Lake Agassiz discharge are potentially resolvable with annual resolution.

The varve record begins during ice withdrawal from the western basin, roughly coincident with ice withdrawal from the southeast shore ca. ~ 10,700 cal ybp [9.5 ^14C ka] (Fisher and Whitman, 1999). Three unique sets of varves that abruptly thicken then rapidly taper, which were deposited ca. 40,600 cal ybp [9.4 ^14C ka], may record the first pulses of Agassiz water into Lake Superior, but this possibility remains speculative. At this time, ice covered most of northeastern Lake Superior. Ice withdrawal from Caribou Basin began around 10,500 cal ybp [9.3 ^14C ka]. A set of one or two hundred thick varves probably records ice re-advance and the formation of the Nipigon moraine beginning around 10,400 cal ybp [9.25 ^14C ka]. The ice margin receded from the northern Lake Superior shore at around 10,200 cal ybp [9.0 ^14C ka]. A lack of correlation within the varve record between 10,200 and 9100 cal ybp suggests that meltwater discharge varied between the inlets and that sediment transport within Lake Superior was a complicated process. A correlative series of 36 anomalously thick varves may record the creation of the Nakina moraine, beginning around 9080 cal ybp [~ 8.15 ^14C ka]. Around 40 years thereafter, ice withdrew north of the drainage divide, so that glacial meltwater and Lake Agassiz overflow circumvented the Great Lakes, spilling directly into Lake Ojibway. Glaciolacustrine sedimentation persisted near the Lake Nipigon inlets for at least another 200 years, finally ending around 8800 cal ybp [~ 7.95 ^14C ka].

Acknowledgements

Support to Thomas C. Johnson from the Weinert Foundation and the University of Minnesota Duluth enabled the recovery and study of the sediment cores. I gratefully acknowledge Thomas Johnson, Captain M. King and crew aboard the R/V Blue Heron for the successful coring operations on Lake Superior, and thank Nigel Wattrus and Deborah Rausch for providing core LS00-3P for analysis. This paper was improved by the reviews from Thomas Johnson, Harvey Thorleifson, and David Rea.

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